AD 734028

10018-7-P

TUNNEL-SITE SELECTION BY REMOTE SENSING TECHNIQUES

Semiannual Report
1 April Through 30 September 1971

BEN DRAKE
PHILIP JACKSON
RALPH MITCHEL
ROGER TURPENING
ROBERT VINCENT

November 1971

UNIVERSITY OF MICHIGAN
1817

RADAR AND OPTICS LABORATORY AND INFRARED AND OPTICS LABORATORY
Willow Run Laboratories
INSTITUTE OF SCIENCE AND TECHNOLOGY

Sponsored by the Advanced Research Projects Agency,
Department of Defense, Washington, D. C., 20301, and
monitored by the U. S. Bureau of Mines.
ARPA Order No. 1579, Amendment 2,
Program Code 1F10

Contract H0210041

3

MISSING PAGE NUMBERS ARE BLANK AND WERE NOT FILMED

NOTICES

Sponsorship. The work reported herein was conducted by the Willow Run Laboratories of the Institute of Science and Technology for the Advanced Research Projects Agency, Department of Defense, Washington, D. C., 20301, and monitored by the U. S. Bureau of Mines, under Contract No. H0210041, ARPA Order No. 1579, Amendment 2, Program Code 1F10. Contracts and grants to The University of Michigan for the support of sponsored research are administered through the Office of the Vice-President for Research.

Distribution. Initial distribution is indicated at the end of this document.

Final Disposition. After this document has served its purpose, it may be destroyed. Please do not return it to the Willow Run Laboratories.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author) Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor, Michigan	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP N/A

3 REPORT TITLE

TUNNEL-SITE SELECTION BY REMOTE SENSING TECHNIQUES

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

Semiannual Report, 1 April Through 30 September 1971

5 AUTHOR(S) (First name, middle initial, last name)

Philip Jackson
Robert Vincent
Ralph Mitchel
Ben Drake
Roger Turpening

6 REPORT DATE	7a. TOTAL NO OF PAGES	7b NO. OF REFS
November 1971	viii + 25	6

8a CONTRACT OR GRANT NO H0210041 b PROJECT NO ARPA Order No. 1579, Amendment 2 c Program Code 1F10 d	9a ORIGINATOR'S REPORT NUMBER(S) 10018-7-P 9b OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10 DISTRIBUTION STATEMENT

11 SUPPLEMENTARY NOTES This contract was monitored by the U. S. Bureau of Mines.	12 SPONSORING MILITARY ACTIVITY Advanced Research Projects Agency Department of Defense Washington, D. C. 20301

13 ABSTRACT

An investigation designed to utilize simultaneously aerial photographs, microwave radar, and multispectral scanners for geologic studies was commenced. In conjunction with ground-truth investigations, we used aerial photographs and data acquired from both passive multispectral scanning and multispectral, multipolar, microwave radar systems in the attempt to construct geologic and lithological maps applicable to the selection of tunnel sites. Specific areas discussed in this report include: (1) Vincent's image-ratioing technique, which provides for the determination of SiO_2 and iron oxide content in specific geologic formations, thus allowing discrimination between different types of surface and subsurface features; (2) a discussion of different types of coherent optical processing techniques available for the enhancement of geologic structures in radar imagery; (3) the potential for using both high-resolution L-band and X-band like- and cross-polarized synthetic-aperture radar imagery in geologic investigations; and (4) a discussion of the present state of the investigation, with recommendations for the improvement of present techniques and the implementation of additional diagnostic aids.

DD FORM 1 NOV 65 1473

UNCLASSIFIED
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Tunnel-site selection						
Remote sensing imagery						
Microwave radar						
Multispectral scanning						
Lithographical maps						
Geologic features						
Image-ratioing techniques						
Optical processing techniques						

10018-7-P

TUNNEL-SITE SELECTION BY REMOTE SENSING TECHNIQUES

Semiannual Report
1 April Through 30 September 1971

BEN DRAKE
PHILIP JACKSON
RALPH MITCHEL
ROGER TURPENING
ROBERT VINCENT

November 1971

RADAR AND OPTICS LABORATORY
AND
INFRARED AND OPTICS LABORATORY
Willow Run Laboratories
INSTITUTE OF SCIENCE AND TECHNOLOGY
THE UNIVERSITY OF MICHIGAN
Ann Arbor, Michigan

FOREWORD

The research reported in this report was performed by Willow Run Laboratories, a unit of The University of Michigan's Institute of Science and Technology. The work was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by the U. S. Bureau of Mines under Contract No. H0210041, ARPA Order No. 1579, Amendment 2, Program Code 1F10. The inclusive dates for this reporting period are 1 April through 30 September 1971. The original Project Officer for this project was Benton L. Tibbitts, who was replaced by James Scott; the current Project Officer is Frank Ruskey. The Willow Run Laboratories' number for this report is 10018-7-P.

The scientists who have contributed to this project throughout the contract period include Ben Drake, Philip Jackson, Ralph Mitchel, Roger Turpening, Robert Vincent, and Thomas Wagner. Roger Turpening is Principal Investigator, while Philip Jackson is Principal Scientist. Section 3 of this report was specifically contributed by Robert Vincent, Section 4 by Ralph Mitchel, and Section 5.2 by Ben Drake. The remainder of the report was written by Philip Jackson.

ABSTRACT

An investigation designed to utilize simultaneously aerial photographs, microwave radar, and multispectral scanners for geologic studies was commenced. In conjunction with ground-truth investigations, we used aerial photographs and data acquired from both passive multispectral scanning and multispectral, multipolar, microwave radar systems in the attempt to construct geologic and lithological maps applicable to the selection of tunnel sites. Specific areas discussed in this report include: (1) Vincent's image-ratioing technique, which provides for the determination of SiO_2 and iron oxide content in specific geologic formations, thus allowing discrimination between different types of surface and subsurface features; (2) a discussion of different types of coherent optical processing techniques available for the enhancement of geologic structures in radar imagery; (3) the potential for using both high-resolution L-band and X-band like- and cross-polarized synthetic-aperture radar imagery in geologic investigations; and (4) a discussion of the present state of the investigation, with recommendations for the improvement of present techniques and the implementation of additional diagnostic aids.

CONTENTS

FIGURES

TUNNEL-SITE SELECTION BY REMOTE SENSING TECHNIQUES
Semiannual Report
1 April Through 30 September 1971

1
SUMMARY

The purpose of this contract is to evaluate signal-enhancement, data-reduction techniques for an airborne system which would utilize simultaneously aerial photographs, microwave radar, and multispectral scanning systems (the latter operating in the 0.32- to 13.5-spectral region). The data acquired from such a system are to be utilized in the construction of both surface and subsurface geologic maps which could be used to predict subsurface conditions in possible tunneling sites. Ground-truth investigations are to be conducted to verify our analyses of the remote sensing data.

For these evaluations, we are using both presently existing and newly acquired remote sensing imagery collected by Willow Run Laboratories. We are presently improving and refining our techniques for collecting and analyzing remote sensing data. Recent advancements in the area include: (1) the development of Vincent's image-ratioing method, which utilizes multispectral imagery to detect differences in the SiO_2 and iron oxide content of geologic formations; and (2) development of high-resolution L-band radar, which allows us to acquire like- and cross-polarized images of both X- and L-band. These developments in remote sensing techniques appear to be applicable to the identification of geologic features. Such new techniques may, in fact, be required before the use of remote sensing in tunnel-site selection is feasible.

We performed a literature search upon the application of airborne radar and multispectral scanning systems to geologic studies in order to avoid duplication of effort, to build upon work performed elsewhere, and to acquaint ourselves generally with the problems involved in using remote sensing for geologic purposes. We have now acquainted ourselves with much of the significant work in the geologic applications of remote sensing and with most sources of current contributions.

At Willow Run Laboratories, compositional remote sensing (the determination of differences in lithology) has been advanced by two new techniques of image ratioing performed upon multispectral data. These techniques allow the discrimination between silicate and nonsilicate geologic formations and the determination of the amount of ferric oxide in given geologic features. Reflectance and emittance calibrations are now being made on rock samples to refine and quantify these methods further.

Several coherent optical processing techniques were applied to available radar imagery in an attempt to reduce the amount of total information and enhance those features applicable to

the identification and interpretation of geologic features. The most successful technique involves an image enhancement method which removes the low spatial frequency portion of the image's spectrum by means of a spatial filter. This method resulted in the capability to delineate more easily the structural edges and lines separating differently-reflecting terrain regions.

During this period, we have also interpreted high-resolution L-band radar imagery along with high-resolution X-band imagery. With like- and cross-polarized returns in each band, we have the capability for both dual-spectral and dual-polarity returns. Interpretation of these radar images from one varied geologic region revealed differences in the imagery related to the texture of the surface and to the substratum under a thin surface layer. The differences shown in the L-band and X-band imagery designate those regions for which ground-truth investigations should be initiated.

With the use of compositional remote sensing and the addition of multispectral and multipolar radar, we presently anticipate that remote sensing will be an economically useful technique to guide field investigations of potential tunnel sites. We now need to quantify more accurately our application of compositional remote sensing, to relate multispectral scanning, radar, and aerial photography more completely to the compositional technique, and to investigate computer selection and color coding for the problem of tunnel-site selection.

2
INTRODUCTION

Sections 3 through 5 of this report discuss specific tasks performed during this reporting period. Sections 3 and 4 present our progress in the area of Imagery Optimization Analysis (Section 1.3 of the contract work statement), while Section 5 consists of a Feasibility Analysis (Section 1.4 of the work statement). Section 6 includes an evaluation of the work already performed, a discussion of its potential for geologic interpretation, and a summary of our plans for continued investigations into the application of remote sensing techniques to the identification of geologic structures. Based upon the increase in knowledge of the geologic features of an area acquired through remote sensing techniques, we hope to improve the present methods at our disposal in order to aid economically in the determination of the most advantageous sites for tunnels.

3
IMAGERY OPTIMIZATION ANALYSIS

Geologic remote sensing has at its disposal two new techniques of image ratioing which are applicable (1) to the discrimination between silicate and nonsilicate geologic formations and (2) to the determination of the amount of ferric oxide in given geologic features. The first technique allows the discrimination of silicate rocks on the basis of a ratio of the radiances in two infrared (IR) channels. Utilizing 25 rock samples selected from R. J. P. Lyon [1], Fig. 1 shows the ratio between channel 1 (8.2 to 10.9 μm) and channel 2 (9.4 to 12.1 μm) and the amount of SiO_2 in percentage of weight, with the ratio symbolized by $R_{1,2}$. The crude correlation between $R_{1,2}$ and the percentage of SiO_2 is evidenced by the straight curve on the graph. The wavelengths of the silicon-oxygen reststrahlen bands are monitored by $R_{1,2}$. The more felsic rocks (those with greater SiO_2 content), generally speaking, have reststrahlen bands (relatively large departures from unit emissivity) at shorter wavelengths than do the mafic rocks (those with lesser SiO_2 content), and therefore $R_{1,2}$ increases with decreasing SiO_2.

The second image-ratioing technique involves a ratio of a channel in the visible green region of the spectrum (channel 5, 0.50 to 0.52 μm) and one in the reflective IR (channel 7, 0.74 to 0.85 μm). This ratio can show the rise in reflectance of ferric oxides from the green to the reflective IR wavelengths. This spectral phenomenon is caused by electronic transitions of the Fe^{3+} ion in the ferric oxides hematite and limonite.

The first technique, utilizing the ratio of two IR channels, is demonstrated in Figs. 2-5, which display infrared images of specially processed scanner data gathered by The University of Michigan aircraft at an altitude of 3000 ft over a sand quarry at Mill Creek, Oklahoma, and over an area near Pisgah Crater in Southern California (also at 3000-ft altitude). The Mill Creek data were gathered on June 25, 1970, at 1000 hours local time, while the data from Pisgah Crater were collected at 0800 hours local time on October 30, 1970. Each of the figures includes analog infrared images of two single-wavelength channels of data, plus an image of the ratio of the radiances in the two channels. The ratio image reflects changes in the chemical composition of the rock targets, primarily changes in their SiO_2 content.

Figure 2 shows images of the Mill Creek sand quarry. In the ratio image (Fig. 2c), all features that appear dark (except for wavy noise lines) are either exposed quartz-sand or sandstone. The outcroppings around the lake in the lower part of the images are sandstone. Geologists from both the United States Geological Survey and The University of Michigan have found almost perfect correlation between the dark regions indicated on the ratio image and quartz-sand or sandstone. This type of discrimination should prove useful in explorations for construction materials, such as sand and gravel.

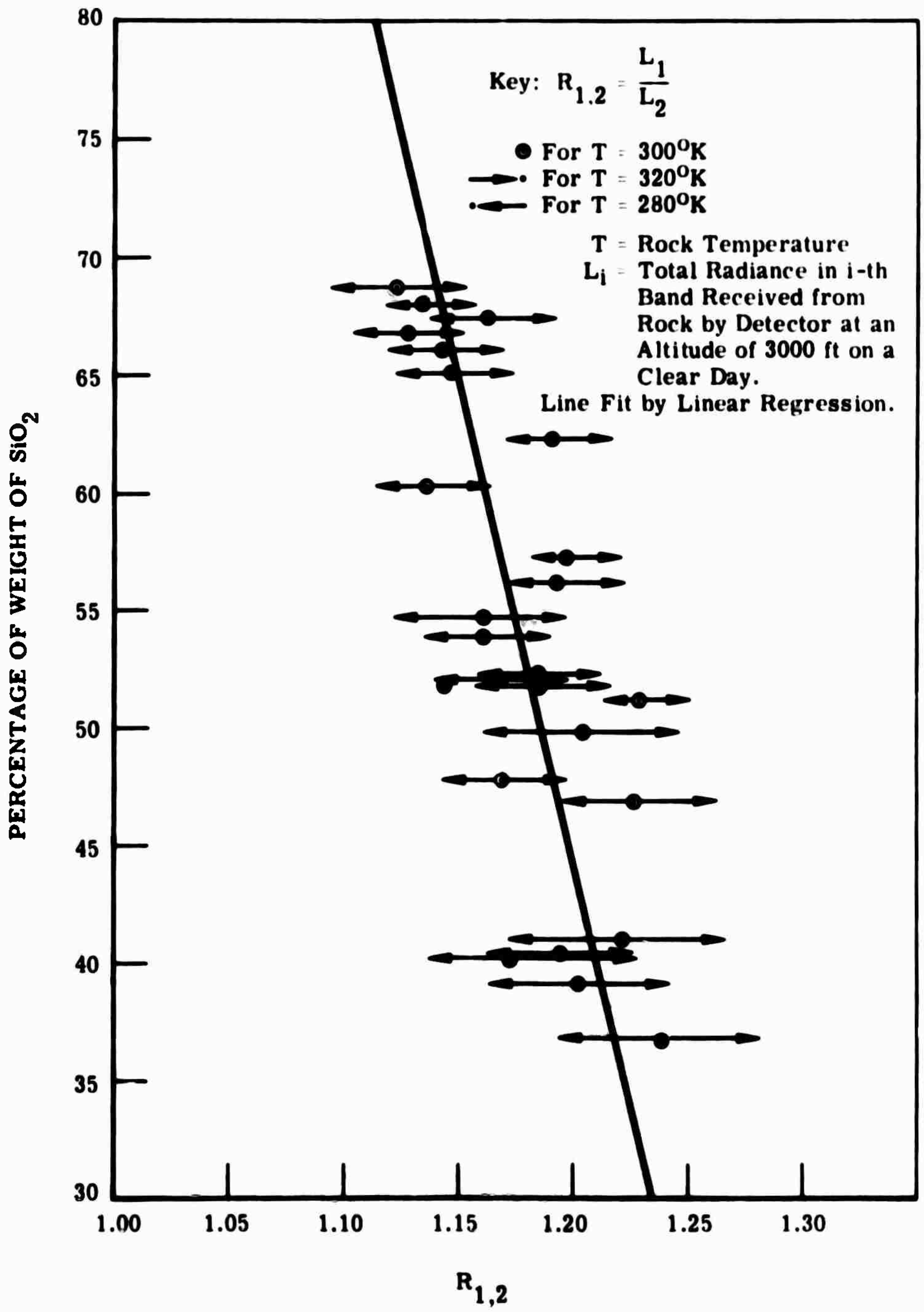
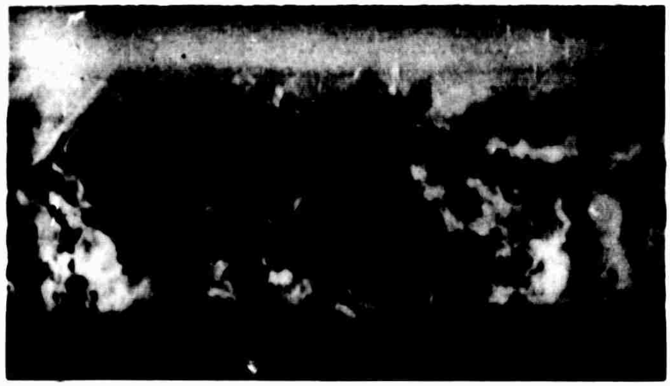
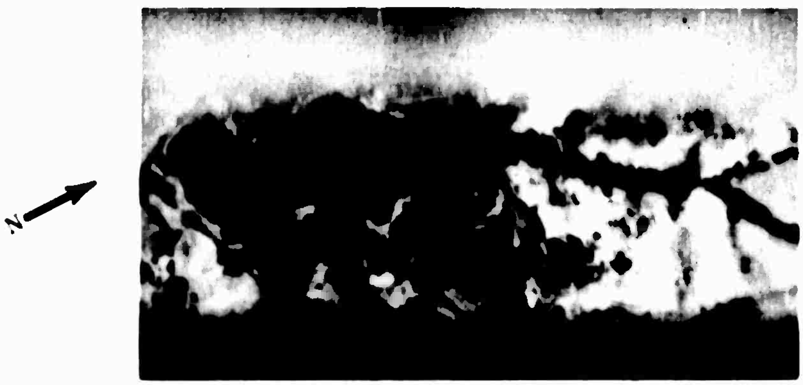


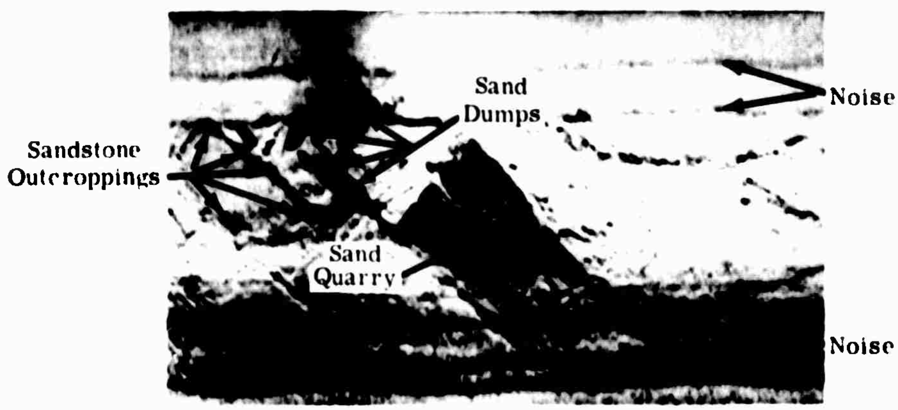
FIGURE 1. RATIO BETWEEN RADIANCES IN CHANNEL 1 AND CHANNEL 2 VERSUS THE PERCENTAGE OF WEIGHT OF SiO_2 IN 25 ROCK SAMPLES. Samples taken from Ref. [1].



(a) Channel 1: 8.2-10.9 μm



(b) Channel 2: 9.4-12.1 μm



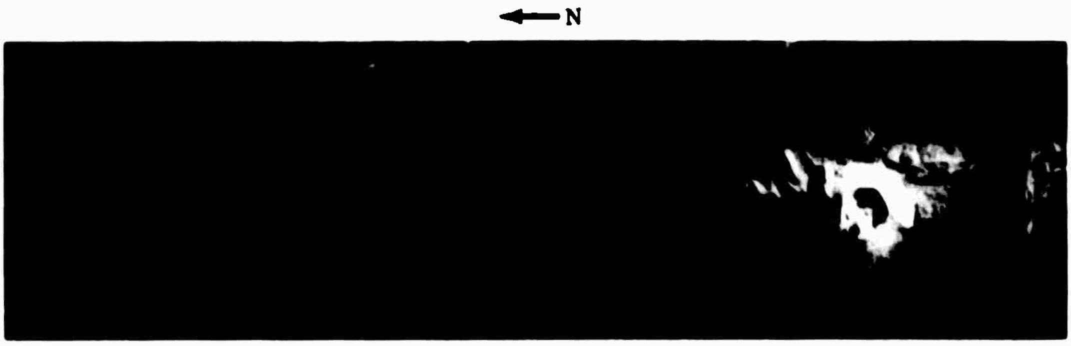
(c) Ratio Image of Channel 1 over 2

FIGURE 2. DISCRIMINATION OF ACIDIC SILICATES NEAR MILL CREEK, OKLAHOMA (SAND QUARRY)

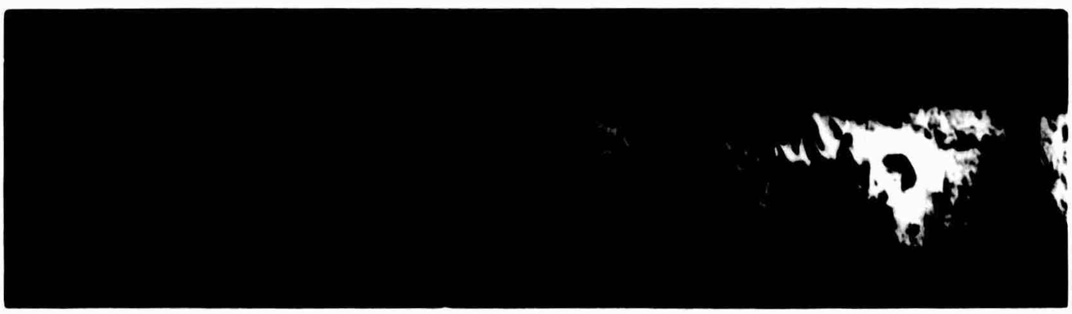
Figure 3 is the first third of a north-to-south flight over Pisgah Crater, located in the right-hand portion of each of the three images. The right half of these images consists primarily of basaltic lava flows which erupted from Pisgah Crater in the late Pleistocene or Recent epochs. These relatively young lava flows (approximately 10,000 to 100,000 years old) erupted in three phases. Although similar in chemical composition, they have quite different surface textures, varying from ropy to blocky. The older fanglomerate in the left half of the images consists primarily of rock fragments from both the basaltic lava and the felsic mountains on both sides of this region. North of the highway, parts of the second eruptive phase of the Pisgah lava are partially covered by alluvium.

With the exception of Pisgah Crater, topographically the highest feature in the images, the single-channel images show very little temperature variation across the scene. The ratio image (Fig. 3c), however, shows considerable variation in the wavelengths of the reststrahlen bands over the same region. Lighter and darker areas on the ratio image indicate reststrahlen bands at longer and shorter wavelengths, respectively. The mafic rocks, which contain lower amounts of SiO_2, should appear bright (indicating a high ratio), and the felsic rocks, containing a higher SiO_2 content, should appear dark (evidence of a low ratio). In the ratio image (Fig. 3c), the basaltic lava appears bright in contrast to the darker tones of the fanglomerate and gravel. The basaltic peninsula near the center of Fig. 3c can easily be discriminated from the surrounding fanglomerate and gravel, whereas the single-channel images (Fig. 3a and 3b) show very low thermal contrast for this feature. In addition, the wind-blown sand extending over the lava just south of the peninsula shows up readily in the ratio image, but is not distinguishable in the single-channel images. In the ratio image, the three bright spots on Pisgah Crater are the only experimental artifacts; these resulted from the much higher temperature on the elevated sunward slopes, which caused clipping of the signal in one of the channels. Patches of exposed basaltic lava north of the highway are also evident in Fig. 3c.

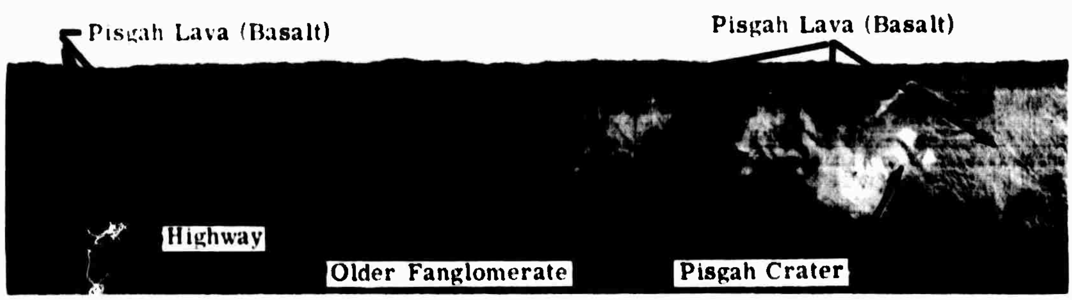
Figure 4 shows the westernmost half of a west-to-east flight line over a region south-southeast of Pisgah Crater. From left to right, the warm region (the light area in the single-channel images) in the extreme western part is a dacitic mountain; the adjacent colder region is fanglomerate and gravel (grading eastwardly to smaller fragments and sand); and the broad, warm region is the basaltic Sunshine lava flow. Just east of the lava flow is alluvium, followed by playa deposits (primarily clay and carbonates) and the southern tip of the basaltic Pisgah lava flow. Once again, the ratio image (Fig. 4c) shows emissivity variations indicative of rock type. The felsic mountains and fanglomerate appear darker than the mafic lava, and the playa material is contrasted sharply against the alluvium. Because the mountains are warmer than other parts of the scene, computational temperature corrections should heighten the contrast between dacite and basalt by lowering the ratio illustrated in the ratio image. In other words, Fig. 4c shows a higher ratio for this section of the image than would be expected on the basis of the wavelengths



(a) Channel 1: 8.2-10.9 μm

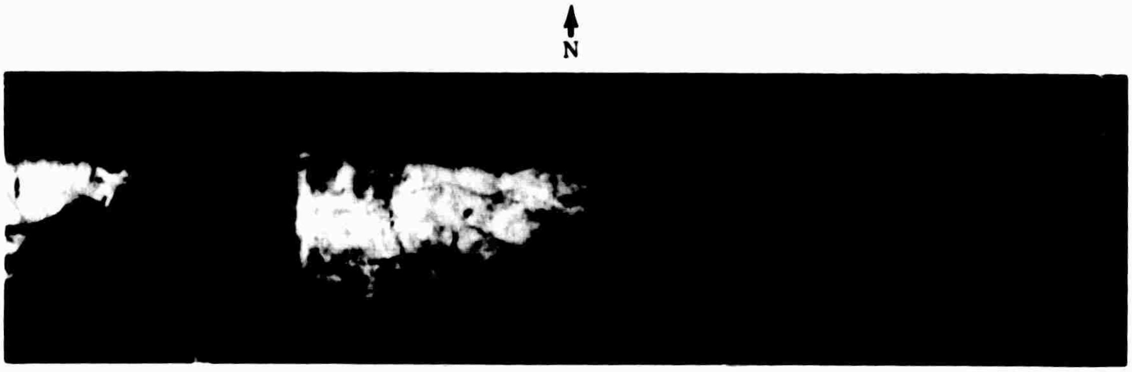


(b) Channel 2: 9.4-12.1 μm



(c) Ratio Image of Channel 1 over 2

FIGURE 3. ANALOG INFRARED IMAGES OF FLIGHT LINE 1, SECTION A NEAR PISGAH CRATER, CALIFORNIA



(a) Channel 1: 8.2-10.9 μm

(b) Channel 2: 9.4-12.1 μm

(c) Ratio Image of Channel 1 over 2

FIGURE 4. ANALOG INFRARED IMAGES OF FLIGHT LINE 2, SECTION A, NEAR PISGAH CRATER, CALIFORNIA

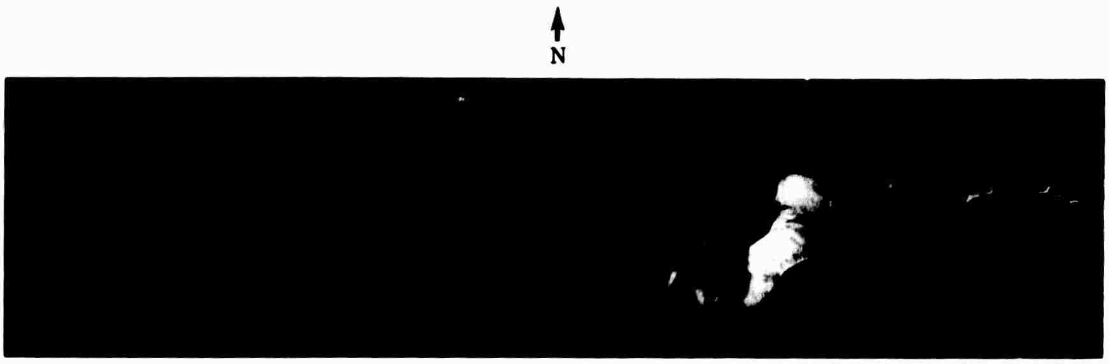
of the reststrahlen bands alone. In contrast, the patchy appearance of the playa is caused solely by emissivity variations, since the temperature is uniform across the floor of Lavic Lake, of which this section is a part.

Figure 5, a continuation of Fig. 4, shows the western half of the flight line across Lavic Lake. From west to east, the first apparent feature is the Pisgah basaltic lava with playa material below it, then alluvium, a basaltic mountain, and an intermittent stream bed, now dry, which has eroded down through the surrounding mountains of basalt. Once again, on the ratio image (Fig. 5c), the southern end of the Pisgah lava flow appears similar to the playa material, and the playa-alluvium boundary is sharply demarcated. On the northern side of the basaltic mountain, the small, dark regions near the center of the image have been confirmed by recent field trip to be felsic outcroppings. The two most prominent dark areas in the stream bed are regions of felsic volcanic tuff, which contain minor amounts of malachite, a copper carbonate. The basaltic mountain in the lower right corner of Fig. 5c appears bright, as did the basaltic lava flow in Fig. 4c. As in the previous ratio images, in Fig. 5c the felsic rocks and rock fragments comprising the alluvium appear to have lower ratios (and therefore appear darker in the ratio image) than do the mafic rocks.

These images show that by ratioing images in the two IR channels 8.2 to 10.9 μm and 9.4 to 12.1 μm, one can enhance emissivity variations in the presence of temperature gradients on the order of 10^{o}C or 15^{o}C without computational temperature corrections. Even in shadowed regions, compositional information is still present in the ratio images. Although temperature-corrected ratio maps are available in digital form, they do not show the contrasts in geologic formations as dramatically as the analog infrared ratio images do.

Figures 6 and 7 illustrate the second ratioing method—i.e., the ratioing of channels in the visible green and the reflective IR spectral regions. Figure 6 shows the same area as that of Fig. 4 (south-southeast of Pisgah Crater), except that the data have been recorded in channel 5 (0.50 to 0.52 μm) and channel 7 (0.74 to 0.85 μm). The ratio of these two spectral regions is sensitive to the presence of iron oxides, with the darker areas corresponding to greater contents of iron oxide. In the ratio image of Fig. 6, the andesite dikes in the dacite porphyry mountain are very clearly outlined, while they are hardly discernible in the single-channel maps of the area. The greater amount of iron oxide in the basaltic lava (as contrasted to that in the alluvium) is also clearly illustrated. Figure 7, which covers the same area as that of Fig. 3, shows that the lava flows around Pisgah Crater vary in iron oxide content, a result in agreement with our analysis of samples recently collected in the field from each of the three eruptive phases.

These ratioing techniques have just recently been developed and are presently being improved. Under the present contract, new laboratory data are being measured, and the results

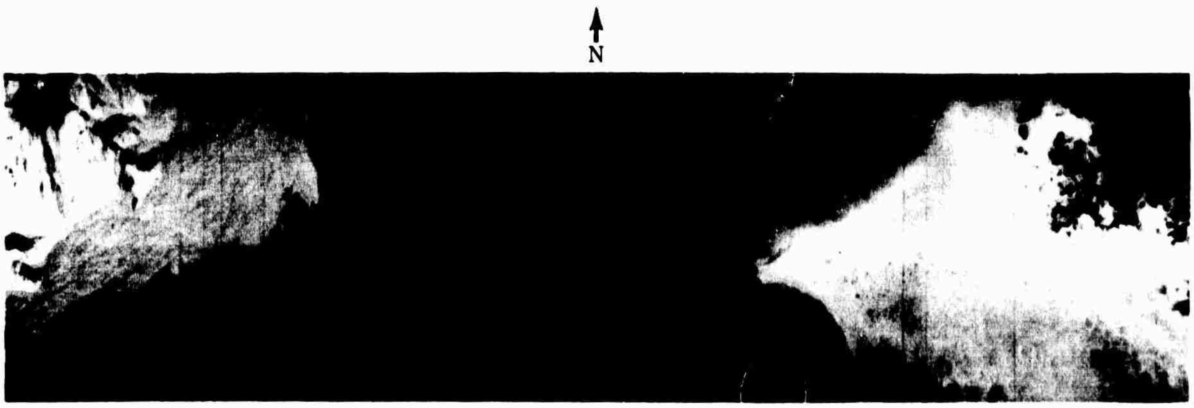


(a) Channel 1: 8.2-10.9 μm

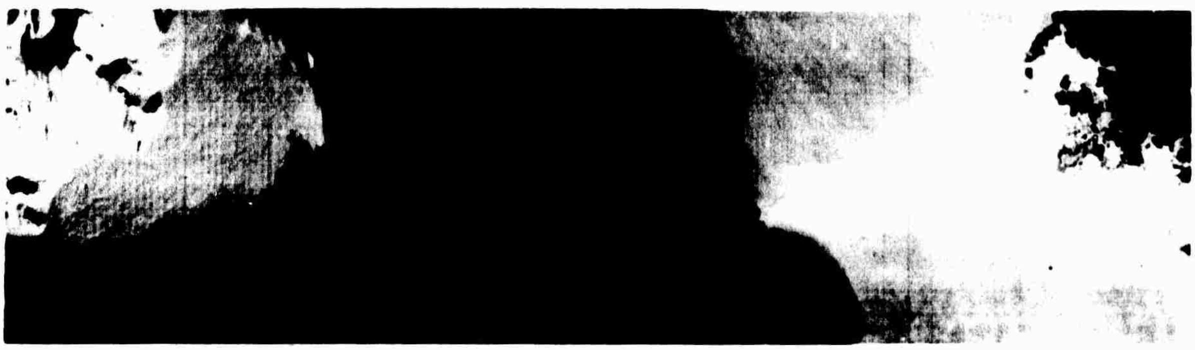
(b) Channel 2: 9.4-12.1 μm

(c) Ratio Image of Channel 1 over 2

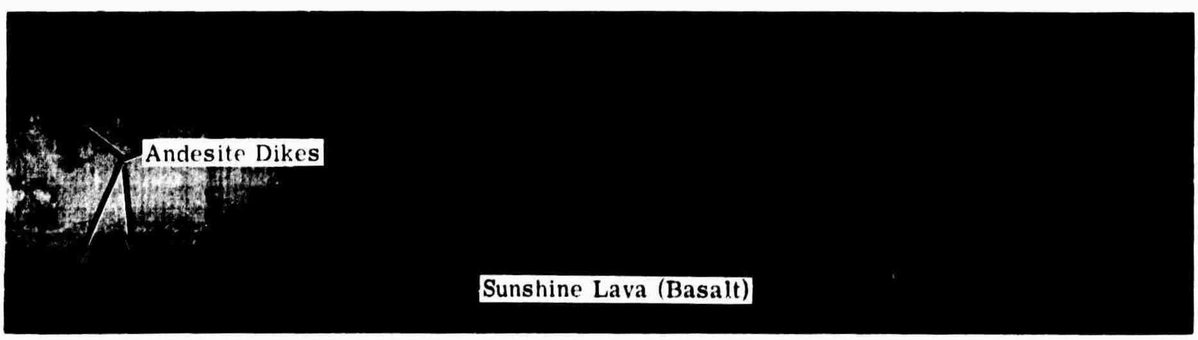
FIGURE 5. ANALOG INFRARED IMAGES OF FLIGHT LINE 2, SECTION B, NEAR PISGAH CRATER, CALIFORNIA



(a) Channel 5: 0.50-0.52 μm

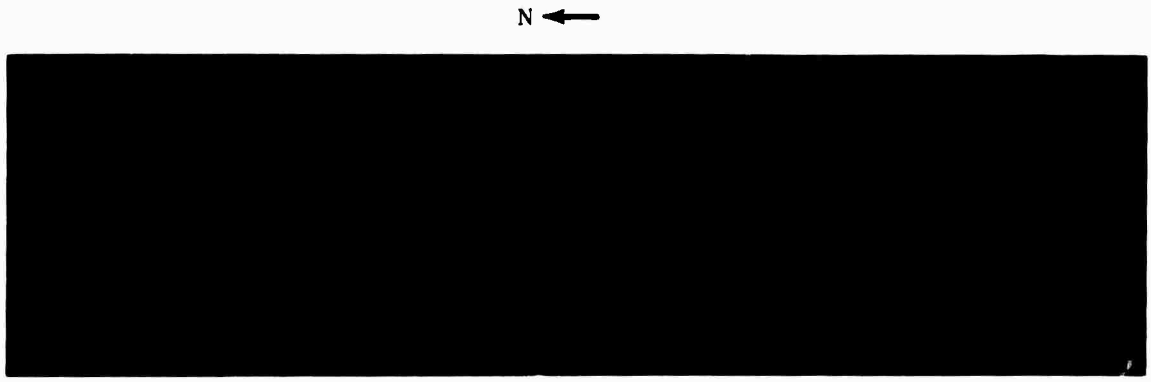


(b) Channel 7: 0.74-0.85 μm



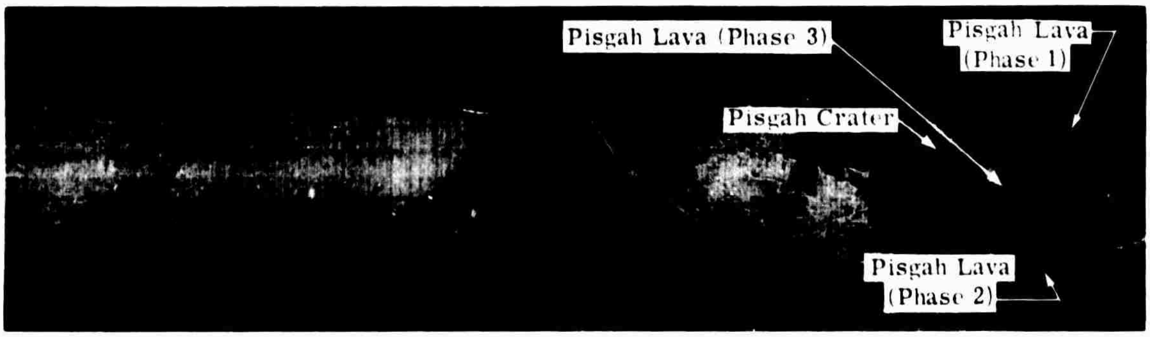
(c) Ratio Image of Channel 5 over 7

FIGURE 6. ANALOG VISIBLE AND NEAR-INFRARED IMAGES OF FLIGHT LINE 2, SECTION A, NEAR PISGAH CRATER, CALIFORNIA



(a) Channel 5: 0.50-0.52 μm

(b) Channel 7: 0.74-0.85 μm



(c) Ratio Image of Channel 5 over 7

FIGURE 7. ANALOG VISIBLE AND NEAR-INFRARED IMAGES OF FLIGHT LINE 1, SECTION A, NEAR PISGAH CRATER, CALIFORNIA

of these measurements should greatly improve our ability to relate the measured $R_{1,2}$ to the chemical parameters of geologic targets. Either the relationship between SiO_2 and $R_{1,2}$ in Fig. 1 will be improved or a different chemical or mineralogical parameter better related to $R_{1,2}$ will be found. In regard to the $R_{5,7}$ ratio technique, several samples from the Pisgah Crater test site are presently undergoing laboratory analyses (both spectral and chemical) in an effort to prove quantitatively the relationship between spectral reflectivity features and the iron oxide content of exposed rock surfaces. It seems likely that the new developments in image-ratioing techniques will lead to improved methods for rapid geologic mapping and lithologic differentiation.

4
OPTICAL PROCESSING FOR ENHANCEMENT OF GEOLOGIC FEATURES

Coherent radar imagery has shown considerable usefulness for all-weather mapping of terrain. The complex scattering mechanism in radar imaging is strongly affected by geomorphic factors and tends to enhance subtle topography and vegetation [2]. The ability of a radar image to reveal small tectonic features and lineaments has been recognized by others: Rowan and Cannon [3] have utilized radar imagery to locate both previously mapped and newly discovered faults in the Mill Creek, Oklahoma area.

Although radar imagery effectively displays a large number of geomorphic features, it still absorbs a considerable amount of a geologist's activity to locate and map tectonic features. Particularly in view of the image coverage afforded by a radar sensor, whereby geological mapping can be extended over much of the earth's surface, the present capacity to collect radar imagery is far beyond that of geologists to examine, analyze, and interpret it adequately.

This problem could be alleviated by processing the imagery to reduce the amount to be examined, allowing the geologist to use his talents for interpretation of the structural signatures. Since the images are two-dimensional, it is natural to consider a form of optical processing which can operate upon the imagery without transformation.

Coherent optical systems, in particular, are suitable for interpreting radar imagery. Along with the capability of analyzing each point of the image simultaneously, coherent optical image-processing systems possess a physically accessible Fourier transform plane, allowing the spectrum of an image to be modified. Thus, linear filtering operations can be performed upon the imagery very rapidly. Examples of the filtering operations commonly performed by a coherent optical-processing system are directional filtering, matched filtering, and image enhancement.

A series of experiments was performed on some high-resolution, synthetic-aperture radar imagery collected by The University of Michigan to evaluate the usefulness of coherent optical processing as an aid to the geologist. The area mapped was near Mill Creek, Oklahoma, an area underlain by gently folded, severely faulted pre-Pennsylvanian rocks, parts of which are covered by Pennsylvanian sandstone and conglomerates of the lower part of the Pontotoc Group. The major faults and folds in these pre-Pennsylvanian rocks run northwest-southeast. In many regions, the conglomerates lack the extensive structures which might reveal offsetting. Rubble along a fault trace appears similar to the parent rock, making the recognition of a fault difficult, even with meticulous field work.

Optical directional filtering experiments were attempted on this imagery with little success. Narrow angular wedges placed in the optical system to modify the spectrum of the radar imagery produced poor discrimination. Although the filtered image had poor contrast, it did contain many streaks identifying lineaments. However, this type of filtering did not effectively reduce he information to be interpreted. Similar results were obtained when a two-dimensional Gaussian slit was used to modify the spectrum of the imagery.

In an effort to obtain better discrimination, optical matched filtering was attempted. The mathematical model that we utilized for the radar energy reflected from a fault trace and recorded on a radar image was as follows:

$$i(x, y) \quad I_0 \operatorname{Rect} \frac{x - x_0(y)}{2\Delta(y)} \operatorname{Rect} \frac{y - y_0}{2a}$$

where
- i the radar imagery reflected from a fault trace and recorded on a radar image
- x coordinate across width of fault trace
- y coordinate along length of fault trace
- I_0 a constant
- 2Δ width of the fault trace
- $2a$ length of the fault trace
- x_0 path taken by a fault trace
- $x_0(y)$ center of fault trace as a function of the location along its length
- y_0 center of fault length

2Δ and x_0 are written as functions of the length y, since the trace may not be of constant width or exactly straight.

We defined probability measures over x_0, Δ, and a, along with the associated probability density functions $f_{x_0}(x)$ and $f_\Delta(x)$ over x, as well as $f_a(y)$ over y. $x_0(y)$ and $\Delta(y)$ are random processes; i.e., for each y they are random variables. We assumed that $f_{x_0}(x)$ is symmetric around some value $x_0(y)$ M (the centroid of a fault trace in the x-direction); that $f_\Delta(x)$ is symmetric at about $\Delta(y)$ λ (average width of a fault trace); and that $f_a(y)$ is symmetric at about some mean value a α (average length of a fault trace).

The probability $i(x, y)$ I_0 is the probability (P) that $x_0 - \Delta \le x \le x_0 + \Delta$ and $-a \le y \le a$, which can be computed to be:

$$P[i(x, y) \quad I_0] \quad \left\{[f_\Delta(-x) - f_\Delta(x)] \cdot F_{x_0}(x)\right\} [F_{-a}(y) - F_a(y)]$$

$$\left\{[F_{-\Delta}(x) - F_\Delta(x)] \cdot f_{x_0}(x)\right\} [F_{-a}(y) - F_a(y)]$$

where F the probability distribution function.

A particular case should, however, be noted; when the fault trace is narrow, having a constant width ($2\Delta \quad 2\epsilon$), where 2ϵ is on the order of the radar image's resolution, we have:

$$P[i(x, y) = i_o] \quad f_{x_o}(x)(2\epsilon)[F_{-a}(y) - F_a(y)]$$

That is, the probability of the fault trace's existence at a particular point is defined in terms of the probability density function of the random variable defining its path.

For the case of uniform noise, a coherent optical correlator using a matched filter in the form of a complex spatial filter can display an output light amplitude distribution proportional to the cross correlation between a reference signal (stored on the filter) and the input image. The results of the experiment utilizing optical matched filtering were mixed. Some of the known faults were not detected. However, with the filter described above, we were able to locate the contact separating the Deese and Dornick Hills formations.

The last experiment performed was image enhancement, designed to eliminate from the radar image that information which is unnecessary to geologic interpretation. The low spatial frequency portion of the image's spectrum was removed by means of a spatial filter. In the processed image, structural edges and lines dividing differently reflecting terrain regions were emphasized. As a result, this experiment allowed geologic interpretation with much less time and effort than that required by the unprocessed pictures.

5
FEASIBILITY ANALYSIS

5.1. DATA

Multifrequency and multipolar radar has been used to investigate the potential for identification and interpretation of geologic features in terms of roughness, general texture, composition, and the presence of features on the order of a wavelength directly below the surface. The resulting imagery is now being used as an aid in geologic interpretation.

Under a NASA contract, during the last week in August The University of Michigan flew both X-band and L-band radar over the Pisgah Crater region in California. Eight signals, like- and cross-polarization of both initial vertical and horizontal orientation, were recorded for each frequency on this flight. Although the actual resolution of the eight images is classified, the images of the Pisgah Crater did reveal differences in the geologic formations of the region. A dried lake, several young lava flows of both blocky and ropy types, alluvial deposits, minor exposures of intrusive igneous rocks, and some apparent drainage features were depicted to varying extents on the different images. Although the geologic causes of some of the differences between different images can be inferred, other differences cannot be explained from examination of the images alone, and therefore a ground-truth investigation could be very helpful.

Although it is anticipated that the images can be presented in a later technical report, they cannot, unfortunately, be reproduced at this time. However, a few of the anomalies in the degree and type of geologic discrimination in different images can be pointed out as examples.

(1) The X-band does not discriminate between lava flows and a thin layer of lava chips lying on silt, while the L-band does discriminate between these two features.

(2) Differences between playa and alluvium show up more in X-band. Possibly this means that the alluvium is shallow and that the L-band is reflecting from a slightly buried feature of suitable roughness.

(3) A dendritic area, which may be a drainage feature, shows up in X-band, but is greatly diminished on the L-band imagery. This pattern does not show up in multispectral imagery, but the reason is unknown.

Perhaps the most important result of utilizing radar images for geologic investigations is that they have provided information not seen previously on multispectral images or aerial

photographs, although ground-truth information should be obtained to explain specific areas located on the radar images. In the comparison of the multispectral and radar images of the Pisgah Crater region, a total of 32 questions were raised concerning the meaning of the differences in discrimination of various geologic features on specific images.

5.2. EFFICIENT UTILIZATION OF REMOTE SENSING IMAGERY

Inspection of radar imagery of various polarizations and wavelengths indicates that the maximum amount of lithological, geomorphological, and structural information is obtained when both like- and cross-polarized images of two distinctly different wavelengths are available. Less information can be acquired from both like- and cross-polarized images of only one wavelength. When one has either like- or cross-polarized images of one wavelength (but not both), a minimum amount of information is obtainable, although even in this case significant geologic data can be derived.

Very little, if any, lithological, geomorphological, or structural information can be acquired from aerial photographs, multispectral imagery, or radar imagery of densely built-up urban areas, unless surface geomorphological patterns (such as a string of lakes or a linear valley) indicative of subsurface lithology can be seen. However, infrequently limited amounts of such information can be obtained from aerial photographs, multispectral imagery, or radar imagery of cultivated fields.

Each of the three remote sensors (aerial photography, multispectral scanners, and radar) commonly yields lithological, geomorphological, and structural data that are not present on the imagery of the other two sensors. If at all possible, aerial photographs, both black-and-white and color, and multispectral and radar imagery of the same area should be obtained.

5.3. RADAR RESOLUTION FOR DIFFERENT WAVELENGTHS AND EVALUATION OF X-BAND IMAGERY BEFORE DEGRADING

Regardless of the resolution of the image, the amount of radar reflection is dependent upon the relationship between the wavelength and the surface-roughness scale of the reflecting surface. For example, road gravel would diffusely reflect 1-cm radar waves and specularly reflect 30-cm waves. If images were degraded to 30- by 30-ft resolution, a large area of gravel would appear light (relatively high reflection) at 1 cm and dark (relatively little reflection) at 30 cm. Both experimental and theoretical analyses show that the different wavelengths are diagnostically useful even when degraded.

Nondegraded X- and L-band imagery has been interpreted for geologic purposes, and tentatively, it appears that more pertinent geologic information can be obtained from those images with higher resolution.

5.4. LITERATURE SEARCH

The literature search was performed to study the application of airborne radar and multispectral scanning systems to geologic studies. We employed sources from the Department of Defense and the National Aeronautics and Space Administration; bibliographies were purchased or otherwise acquired, pertinent current journals and government reports scanned, and basic texts studied. The purposes of the search were to avoid duplication of effort, to build upon and include in our evaluation work which had been performed elsewhere, and to acquaint ourselves with the problems and possible approaches to their solutions.

Although we have acquired a general knowledge of the state of the art and of the sources of current contributions, we still have much to learn. For example, photogeology has been developed to a highly sophisticated discipline requiring much experience. Since our project is concerned with developing and evaluating an extension of photogeology, we must be certain to use properly the techniques and potential of photogeology for extended applications with multispectral and radar data. Photogeology is only one of the areas in which continuous literature study is required.

A secondary objective of the literature search has been to study the geologic problems of tunneling. Thus far, we have studied the general problems that tunneling presents in order to be aware both of the geologic features to be sought and those to be avoided when tunneling sites are selected.

In subsequent reporting periods, our emphasis will be on current literature dealing with the general area of remote sensing as applied to geologic research.

5.5. THE FEASIBILITY OF EXTENDING 25-db TONE AND TEXTURE OF RADAR RECORDINGS TO 60-70 db

Essentially, the signal film recorded from synthetic-aperture radar is in a frequency with relatively wide range (~60 db) (Brown and Porcello, 1969 [4]; Cutrona, et al., 1966 [5]). When the output of the radar optical processor is viewed directly, the wide dynamic range is retained: a very bright spot in the output will stun the eye just as shining a flashlight directly into it will. When an output film is made of the radar scene, the bright spots either bloom, or the exposure and development of the film is so controlled that the brightness is reduced to about 20 db.

A new method of making a hologram of the radar output has recently been developed at Willow Run Laboratories, so that the hologram may be viewed through rather simple optics which retain the wide dynamic range. Although this new type of hologram provides an extremely striking effect, it is not evident at this time that it will aid geologic interpretation.

Under another contract, the Radar and Optics Division has designed and is installing a digitizing system which uses an image dissector. This system will digitize images in the output

plane of the radar optical processor, so that the wide dynamic range will be available for digitizing. Time of completion is presently estimated to be from two to three months. We anticipate digitizing radar images of regions being studied and using digital computation to perform image subtraction or ratioing.

6
PRESENT STATE OF THE INVESTIGATION, POTENTIAL APPLICATIONS, AND PLANS

In most of the specific tasks delineated in the contract, significant advances have been accomplished at the Willow Run Laboratories during this reporting period. One of the most important advances is compositional remote sensing made possible by Vincent's ratioing method, which was only hypothetical at the time the work for this contract was proposed. This ratioing technique has produced a new dimension in geologic remote sensing.

Only certain types of surface lithologies can now be identified, but the ratioing method is potentially able to differentiate between all rock types in which the reflectance or emittance spectra differ. An example of the potential of this method is the discovery of andesite dikes by compositionally sensing their ferric oxide content in a NASA test region which previously had been thoroughly investigated both by remote sensing and ground mapping.

The extension of our high-resolution radar to L-band, with the resulting capability of producing multispectral and multipolar images, has enabled us to locate geologic features not previously identified. We plan to utilize a ratioing technique upon these radar images similar to that used by Vincent upon multispectral imagery.

Rowan, et al. [6] of the U. S. Geological Survey have delineated fault zones in predawn thermal-IR imagery, an accomplishment which may have significant applications to the selection of tunneling sites. The identification of fault zones and use of the thermal inertia properties of different rock types should extend the capabilities of geologic remote sensing.

In addition, digital and analog computations, such as ratioing, color coding, and possibly optical processing, should aid the geologist in interpreting remote sensing data.

Our task now is not only to improve these individual approaches, but to coordinate them to learn both their limitations and their potentials in selecting accurately and economically the best tunnel sites. To make this evaluation, we are concentrating on geologic areas for which we already have much imagery, one of which is the Pisgah Crater region in California. Although it is not a region through which one would expect to build tunnels, it does contain varied geologic features which are challenging to identify and analyze and which might be encountered in some potential tunnel sites.

Our plans are to continue investigating and, if possible, improving specific remote sensing techniques. We intend to continue the detailed geologic interpretation of remote sensing data and to evaluate our interpretations through ground-truth investigations of those areas of significant geologic interest for which we already have extensive data. At present, these areas include

the Pisgah Crater region, the Niagara escarpment region in southern Ontario, and the Arbuckle Mountains near Mill Creek, Oklahoma. Possibly after conference with the Project Officer, NASA flights can be requested for the purposes of this project.

REFERENCES

1. R. J. P. Lyon, Evaluation of Infrared Spectrophotometry for Compositional Analysis of Lunar and Planetary Soils: Rough and Powdered Surfaces (Final Report, Part II under NASA Contract NASr-49(04)), Stanford Research Institute, Menlo Park, California, 1964.

2. H. O. Rydstrom, "Interpreting Local Geology from Radar," Geol. Soc. Amer. Bull., Vol. 78, 1967, pp. 429-436.

3. L. C. Rowan and P. J. Cannon, "Remote-Sensing Investigations Near Mill Creek, Oklahoma," Oklahoma Geol. Notes, Vol. 30, No. 6, December 1970.

4. W. M. Brown and L. J. Porcello, "An Introduction to Synthetic-Aperture Radar," IEEE Spectrum, Vol. 6, No. 9, September 1969.

5. L. J. Cutrona, E. N. Leith, L. J. Porcello, and W. E. Vivian, "On the Application of Coherent Optical Processing Techniques to Synthetic Aperture Radar," Proc. IEEE, Vol. 54, No. 8, August 1966.

6. L. C. Rowan, T. W. Offield, K. Watson, P. J. Cannon, and R. D. Watson, "Thermal Infrared Investigations, Arbuckle Mountains, Oklahoma," Geol. Soc. Amer. Bull., Vol. 81, December 1970, pp. 3549-3562.